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M. Kusaka
*Matsushita Refrigeration Company*

K. Nakatani
*Matsushita Refrigeration Company*

T. Takatani
*Matsushita Refrigeration Company*

# *THE DEVELOPMENT OF THE ENERGY-SAVING TECHNOLOGY BY THE COMPOSITION CONTROL OF R407C*

**Michiyoshi Kusaka , Kazuo Nakatani , Takayuki Takatani**

**Air Conditioning Systems Office**
**Engineering Center**
**Matsushita Refrigeration Company**
**4-2-5, Takaida Hondori, Higashi-Osaka City, Osaka Pref., Japan 577-8501**
**Phone : +81-6-6784-3917, Fax : +81-6-6784-3944**
**E-mail : kusaka@mrc.mei.co.jp, nakatani@mrc.mei.co.jp, takatani@mrc.mei.co.jp**

## ABSTRACT

The purpose of this study is to develop a higher performance refrigeration system with R407C {R32/R125/R134a(23/25/52wt%)},using a technique of capacity control by varying the zeotropic refrigerant composition. Then, we applied this rectification system to a packaged air conditioner. As a result, we were able to vary the refrigerant composition from 23/25/52 wt% to 6/14/80 wt%, and thus to control the system capacity. It was confirmed that the annual SEER increased about 25% in the comparison with an ordinary low-cost system using a constant-speed compressor. This performance is comparable to that of the high-cost system with a variable-speed compressor.

## INTRODUCTION

In recent years, it is an important issue to protect the ozone layer and to prevent global warming from the viewpoint of environmental protection of the earth. Regarding the protection of the ozone layer, the phase-out schedules of HCFCs were started in 1996, and they are almost totally eliminated by the year 2020.

On the other hand, regarding the prevention of global warming, it is also an important issue for air conditioners to make the equipment higher in efficiency as well as to use suitable alternative refrigerants in order to reduce $CO_2$ emissions.

Under the circumstances, we have decided to use R407C{R32/125/134a(23/25/52wt%)}as R22 alternative refrigerant for packaged air conditioner in Japan.

The inverter control of compressor can be mentioned as the main energy saving technology for packaged air conditioners in Japan. However, inverter packaged air conditioners are not so much propagating because of high initial costs and the necessity of developing such equipment(inverter compressors and inverter control circuits). Under the circumstances, ordinary low-cost systems with constant speed compressor are mainly used in the packaged air conditioner market.

Accordingly, the present study has developed a refrigerant composition control system which improves the system performance in capacity saved operation just like inverter system under lower air conditioning load by using a constant speed system thereby realizing remarkable improvement of the annual SEER.

## COMPOSITION CONTROL OF REFRIGERANT

In the present study, the refrigerant composition circulated in the refrigeration system is controlled according to the air conditioning load by using the zeotropic characteristics of R407C in order to greatly improve the system performance. As shown in Fig. 1, separating R407C(R32/R125/R134a) into lower boiling point component R32/R125 and higher boiling point component R134a, the air conditioning system is operated with R134a-rich while storing the R32/R125-rich in the reservoir during lower air conditioning load operation requiring less air conditioning capacity. In this way, the capacity is saved form the thermophysical properties of refrigerant and then system EER improvement as shown in Fig. 2. Furthermore, the improvement of compressor efficiency can be expected because the condensing pressure is lowered. Also, the system efficiency will be improved since it is possible to reduce the ON/OFF operation losses of the compressor.

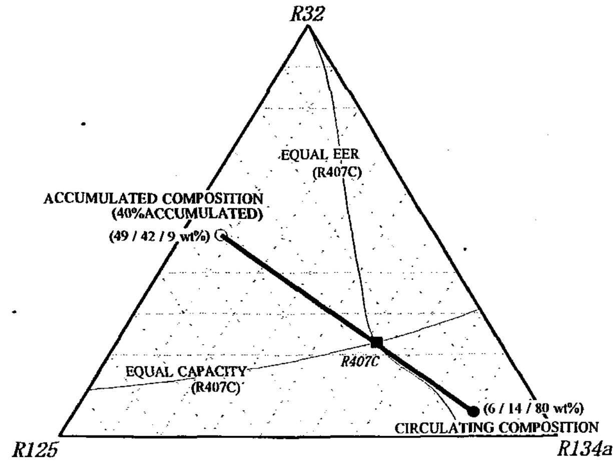


Fig. 1 R407-Series Diagram

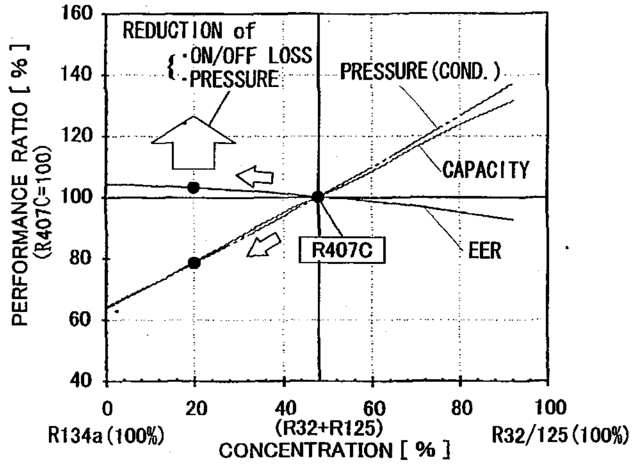


Fig. 2 Theoretical Cycle Characteristics

## RECTIFICATION SEPARATION

A rectification separation was employed as the composition control method from the viewpoint of performance and cost.

Rectification separation is to separate the component into lower boiling point component and higher boiling point component by utilizing the difference in boiling point between each composition of the zeotropic mixtures (Table 1). A rectifier is used for rectification separation while the gas and liquid are subjected to counter-flow contact in it. At that time, the component is separated into higher boiling point component and lower boiling point component. The rectifier is filled with a packing in order to increase the gas and liquid contact area.

In the present study, the lower boiling point component R32/R125 is separated and stored in an attempt to ensure capacity saving and high efficiency operation.

Fig. 3 shows the principle of rectification separation in the rectifier.

The following three elements can be mentioned as the basic constituents of the rectification separation system including the aforementioned rectifier.

Table 1 Boiling Point

| | Boiling Point | |
|---|---|---|
| R32 | -51.65 ℃ | Lower |
| R125 | -48.14 ℃ | Lower |
| R134a | -26.07 ℃ | Higher |

*)REFPROP Ver. 6.01

① Rectifier : rectification separation is performed.
② Upper Reservoir : the separated lower boiling point component is stored.
③ Condenser : the lower boiling point gas component separated at top of the rectifier is condensed.

Particularly, the rectifier is an important component part on which the separation performance depends. The selection of an rectifier packing as well as optimization of the diameter and height of the rectifier packing are very important points in the design of a high performance rectifier.

As packings available at present, there are Dixon packing and MacMahon packing which are generally used at chemical plants, but these packing are high-cost.

Accordingly, the present study intended to develop low-cost packings and to optimize the rectifier specification while ensuring excellent separation performance.

Also, the following can be mentioned as the important points of development when connecting the rectification separation system to the refrigeration cycle.

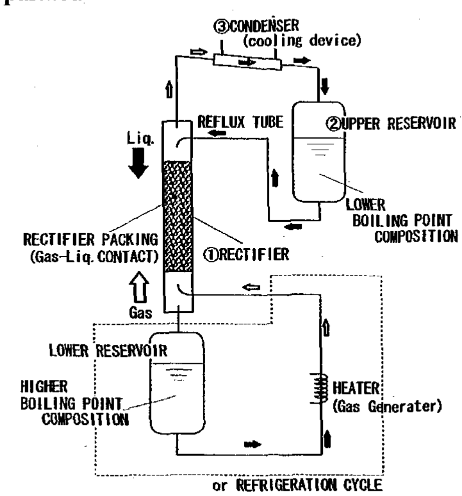


Fig. 3 Principle of Rectification Separation

-Assurance of rectifier bottom gas generating source.
-Assurance of rectifier top gas cooling source and condenser.

## Development of Low-Cost and High Performance Packing

The following can be mentioned as the characteristics generally required for the packings.

- A sufficient contact area between the gas and liquid.
- A large void space.
- Divagation hardly takes place.
- Low cost.

We have evaluated nearly 30 types of rectifier packings taking the above-mentioned requirements into consideration.

The separation performance was evaluated with the use of NTP (Number of Theoretical Plates) and R134a separation concentration per unit time. In this case, NTP is an approximate index by means of calculation based upon R407C vapor-liquid equilibrium, and the higher the value the better the performance.

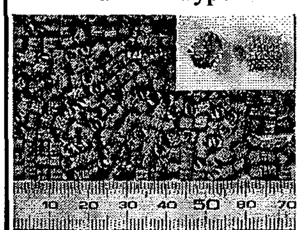
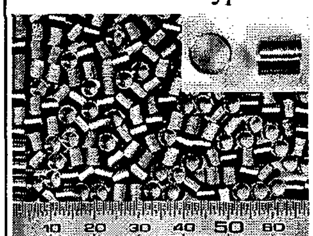
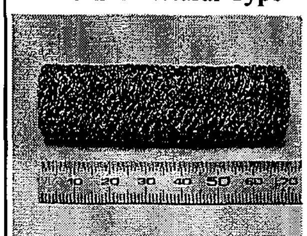
The comparison is shown in Table 2. As a result of the examination, SUS coiled packing (random type) and SUS mesh wound packing (uni-structural type) were selected because their performance is nearly equivalent to that of Dixon packing with which the cost can be considerably reduced.

Particularly, it is possible to greatly reduce the cost with SUS mesh wound packing, and this material is uni-structural and therefore effective to improve the workability of filling in rectifier formation.

Also, the SUS mesh wound packing hardly divagates during the filling operation and there is almost no problem of performance lowering due to divagation.

Accordingly, we have decided to employ SUS mesh wound packing for the purpose of the system investigation as mentioned in the following.

Table 2 Rectifier Packings

| | Dixon Packing | SUS coiled Packing | SUS mesh wound Packing |
|---|---|---|---|
| Picture of Packing [mm] | Random Type  | Random Type  | Uni-Structural Type  |
| Specification | $\phi$ 3mm × L3mm<br>100mesh<br>2380 pieces | $\phi$ 4mm × L4mm<br>$\phi$ wire 0.2mm<br>1340 pieces | $\phi$ 23mm × L210mm<br>(70mm × 3pieces) |
| Performance (NTP) | 6.5 | 4.7 | 4.7 |
| Composition (R134a) of Lower Reservoir | 52wt% → 73wt% | 52wt% → 71wt% | 52wt% → 71wt% |
| Cost / Volume (ratio) | 1 | 1/13 | 1/25 |
| Evaluation | × | ○ | ◎ |
| Note | Conventional | Development | Development |

*1)Input Power of Gas Generator ··· 225 [W]
2)Separation Time ··· 3[Hour]

## Optimization of Rectifier Specification

The rectifier dimensions (rectifier packing diameter × height ) have been optimized.

Fig. 4 shows the rectifier diameter on the horizontal axis and the R134a concentration of lower reservoir on the vertical axis.

In optimization of the rectifier packing diameter, the separation performance is at the peak when the diameter is $\phi$29 mm.

Generally, it is possible to increase the volumes of the gas ascending and the reflux liquid descending in the rectifier with the rectifier packing diameter increased. Therefore, the treating volume per unit time increases and the separation tends to make progress. However, as shown in Fig. 5, the reflux liquid from the reflux tube at the rectifier top goes down to the center of the rectifier and then gradually spreads in the direction of the rectifier packing diameter as it comes down. That is, as the rectifier packing diameter becomes larger, only ascending gas exists near the periphery of the rectifier top, and the gas does not come in contact with the reflux liquid. Therefore, it can be considered that the effective gas-liquid contact area becomes decreased resulting in lowering of the separation performance when the rectifier packing diameter is larger than $\phi$29mm .

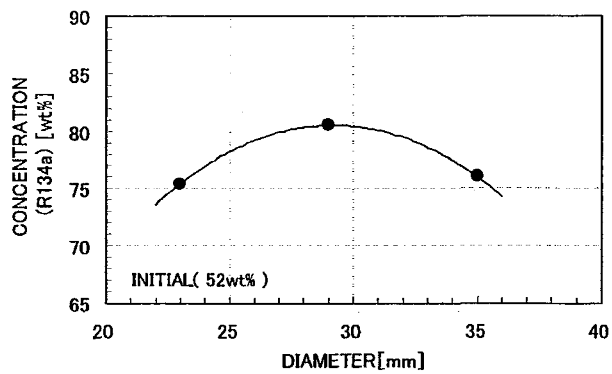



Fig. 4 Rectifier Packing Diameter Characteristics

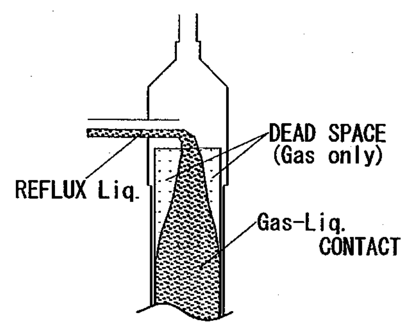



Fig. 5 Rectifier Top Structure

Fig. 6 shows the height of rectifier packing on the horizontal axis and the R134a concentration of lower reservoir on the vertical axis.

In optimization of the rectifier packing height, the longer the rectifier packing height the higher the R134a concentration in the circulating composition becomes, and then the progress of separation is confirmed. The R134a concentration of the upper reservoir is nearly at the separation limit when the rectifier height is 260 mm. Therefore, the effect obtained by making the rectifier packing longer than this may be very slight.

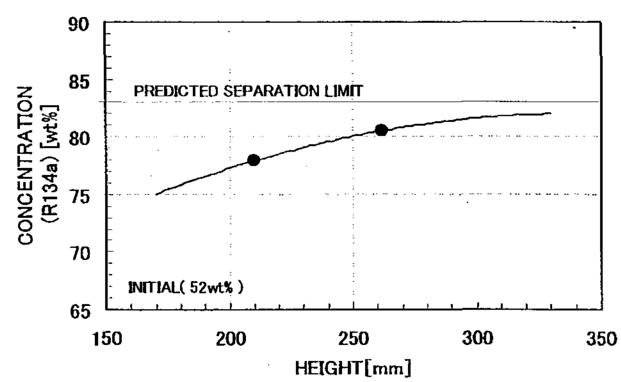



Fig. 6 Rectifier Packing Height Characteristics

From the results thus obtained, we have decided the rectifier packing specification as follows:

- Diameter : $\phi$ 29mm (10/8" t=1.2mm)
- Height : L 260mm (packing height)

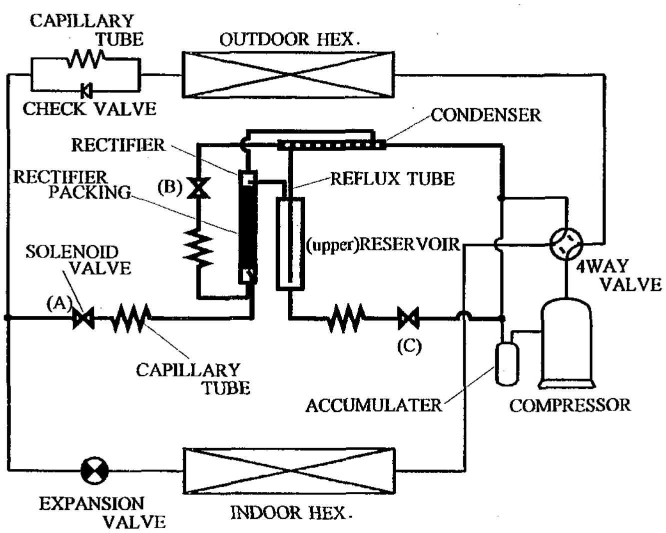
## DEVELOPMENT OF REFRIGERATION CYCLE EQUIPPED WITH RECTIFICATION SEPARATION SYSTEM

The specification for installing the newly developed rectification separation system onto the refrigeration cycle is shown in Fig. 7.

As shown in the figure, the gas component of two-phase refrigerant with a part of the high pressure liquid refrigerant reduced to an intermediate pressure level is used as the rectifier bottom gas generating source in the rectification separation system, and also, the liquid component of two-phase refrigerant similarly with a part of the high pressure liquid refrigerant reduced to an intermediate pressure level is mixed with the reflux liquid from the rectifier top and is reduced in pressure to use the latent heat as the rectifier top gas cooling source.

Also, a compact double-tubed condenser with inner tube for evaporating and outer tube for condensing, using new type of tube, has been developed as a condenser for rectifier top gas condensing.

Such a system composition has enabled us to create a high performance rectification separation system which is compact and able to secure the cooling source as well as the rectifier bottom inflow gas and also capable of stable separation. (Fig. 8)




SOLENOID VALVE OPERATION

| | A | B | C |
|---|---|---|---|
| NOMAL mode | CLOSE | OPEN | CLOSE |
| SEPARATION mode | OPEN | OPEN | CLOSE |
| HOLD mode | CLOSE | CLOSE | CLOSE |
| MIX mode | CLOSE | CLOSE | OPEN |

Fig. 7 Schematic Diagram of Rectification Separation Cycle

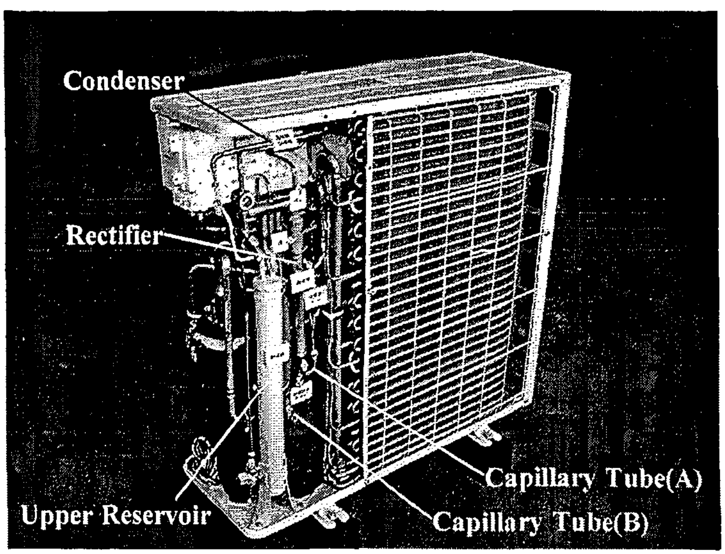



Fig. 8 Prototype

## SYSTEM PERFORMANCE

The result of rectification separation (cooling) in the 3HP system is shown here.

Fig. 9 shows the change of the circulating composition (lower reservoir).

It can be confirmed that the R134a concentration has been condensed to about 80wt% in 120 minutes of separating operation. Here, the initial R134a concentration is about 46wt% (52wt% charged) because of change in composition due to the existence of surplus higher boiling point refrigerant in the accumulator.

It can also be confirmed that the R134a concentration has been already subjected to separation up to about 76wt% in about 60 min. That is, the separation percentage has been already about 90% level of that obtained in 120 minutes.

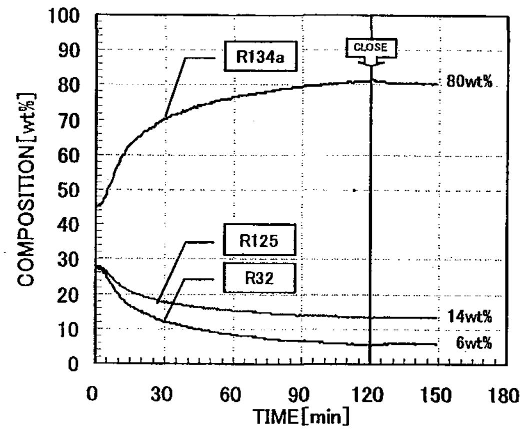


Fig. 9 Composition Change

The changes of capacity and system EER as against the change of circulating composition are shown in Fig. 10.

After start of the separation, the capacity is soon decreased to about 80% level of that in normal mode. This is because the refrigerant is stored in the reservoir after start of the separation mode, causing the refrigerant in the main circuit to decrease in a short time, and of the expansion valve opening enlarged on start of the separation mode. After that, the capacity is gradually decreased as the separation goes on.

Also, system EER is slightly decreased immediately after start of the separation mode, but it is confirmed that such a tendency is improved with progress of the separation.

After completion of the separation mode, the capacity is slightly increased with the separation circuit closed (hold mode) and is stabilized at about 83% of that in normal mode.

Also, the system EER is greatly increased as compared to the separation mode and is stabilized at about 126% of that in normal mode.

This is because the separating operation includes bypassing of the high pressure liquid refrigerant to a low pressure level in the separation mode, and so the capacity is decreased due to reduction of the refrigerant passing through the evaporator. That is, EER is similarly decreased as the capacity is decreased due to liquid bypassing.

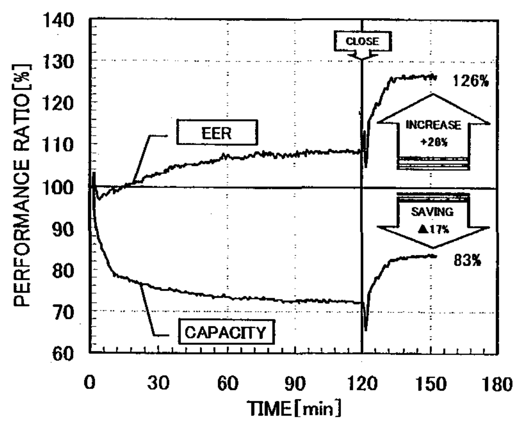


Fig. 10 Performance Change

Fig. 11 shows the changes of discharge and suction pressures of the compressor in the separation mode.

It can be confirmed that both discharge and suction pressures are decreased with progress of the separation. As compared to the before-separation level, the discharge pressure decreased by about 0.8MPa while the suction pressure by about 0.17MPa.

This means that the ON/OFF operations of the compressor frequently taking place for high pressure protection can be lessened even during such a severe operation subjected to generation of high pressures as in higher air conditioning load operation. Therefore it gives rise to the improvement of suitability and reliability of the system.

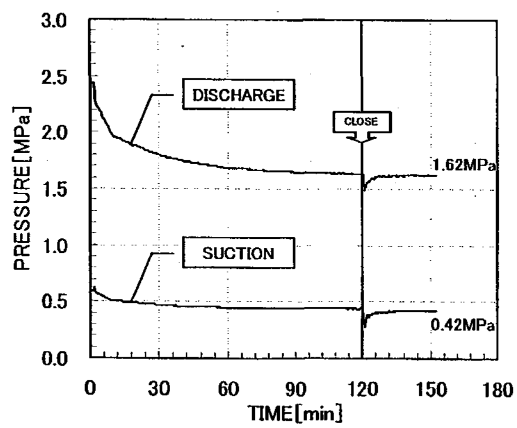


Fig. 11 Pressure Change

We do not refer to the heating operation since the explanation is almost the same as for the cooling operation.

## ANALYSIS

The result of analysis made on the factors of system EER improvement in capacity saving by composition control is shown here. Table 3 is the performance comparison before and after composition control in cooling operation.

Table 3 Performance (Cooling)

| | Before (normal mode) | After (hold mode) |
|---|---|---|
| Cooling Capacity (Ratio) [%] | 100 | 83 |
| System EER (Ratio)[%] | 100 | *126* |
| Discharge Pressure [MPa] | 2.44 | *1.62* |
| Suction Pressure [MPa] | 0.58 | *0.42* |
| Compression Ratio [-] | 4.12 (100) | *3.83 (91)* |
| Circulating Composition (R32/R125/R134a) [wt%] | 28/28/44 | 6/14/80 |

As shown in Table 3, it can be confirmed that the pressure change as well as the composition ratio change are very remarkable with respect to the cycle performance before (normal mode) and after (hold mode) composition control.

Therefore, the following can be mentioned as the main factors of efficiency improvement from the analysis of the influences to the system performance.

- Improvement of theoretical coefficient of performance (COP) on P-h diagram due to pressure change (reduction of discharge pressure in particular).
- Improvement of compressor efficiency in relation to the reduction of compression ratio.
- Improvement of theoretical COP with respect to thermophysical property of refrigerant.
- Others
  (improvement of heat transfer coefficient in relation to the reduction of circulating composition R125, etc.)

Fig 12 shows the above-mentioned factors. Particularly, it has been confirmed that the improvement of theoretical COP on P-h diagram in relation to the reduction of discharge pressure is remarkable.

We do not refer to the heating operation since the explanation is almost the same as for the cooling operation.

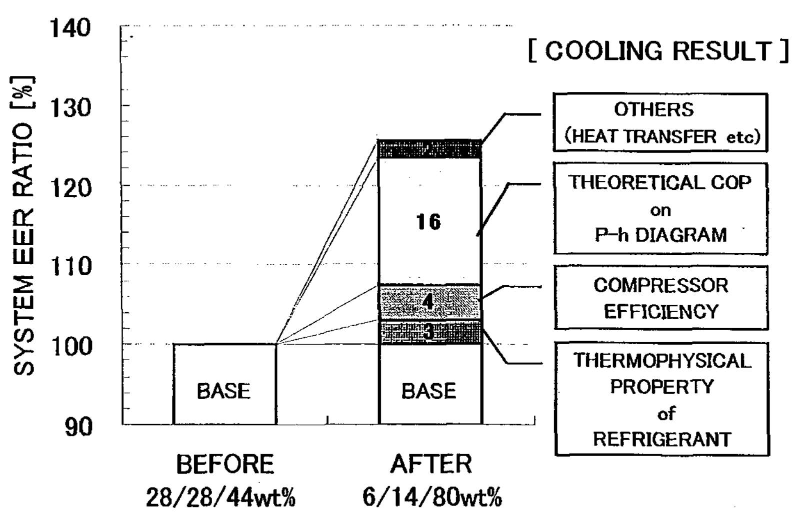



Fig. 12 Factors of System Performance Improvement

## SEER

Fig. 13 shows the performance comparison between the conventional system(ON/OFF only) and the composition controlled system in cooling operation. The capacity ratio is shown on the horizontal axis and the system efficiency ratio on the vertical axis. Regarding the heating operation, the explanation is omitted here.

The capacity saving ratio by composition control is about 17%, and for saving the capacity much more, compressor ON/OFF operation must be used together with the operation the same as in the conventional system.

The cooling/heating SEER and annual SEER have been calculated according to the relations of air conditioning load and operating time based upon the above-mentioned result (using in-company evaluation method). The comparison with the conventional system is shown in Table 4.

As a result of calculation, it has been confirmed that the energy saving effect of this composition controlled system was improved by about 25% in annual SEER and by improved 25% with respect to both cooling and heating SEER as compared with the conventional system.

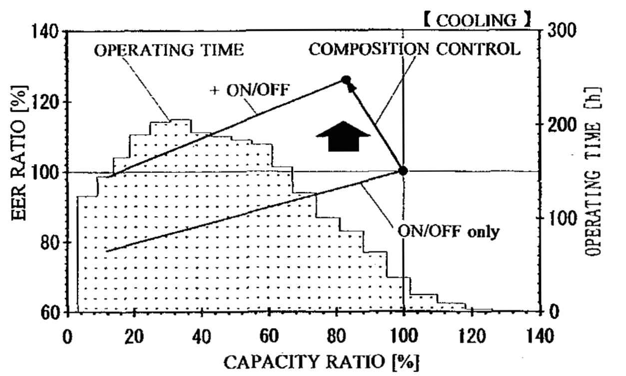



Fig. 13 Capacity - EER Characteristics

Table 4 SEER Comparison

| | ON/OFF Only | Composition Control |
|---|---|---|
| Cooling SEER | 100 | 125 |
| Heating SEER | 100 | 125 |
| Annual SEER | 100 | 125 |

## CONCLUSIONS

The results of the present study are summarized in the following.

(1) A compact high efficient rectification separation system has been developed.

(2) A low cost high efficient packing has been developed.
It is nearly equivalent in performance to the conventional packing and its cost is about 1/25.

(3) The specification of installation onto the refrigeration cycle has been established.

(4) The operation has been tested on a prototype and it has been confirmed that the R134a circulating composition ratio can be changed from charging composition 52wt% to about 80%.

(5) The improvements of capacity saving ratio by 17~25%, system efficiency in capacity saving by about 26% and annual SEER by about 25% have been achieved by the composition control.

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